IOTA Nonlinear Integrable Optics Experiment: Landau Damping (NIOLD)

PERSONNEL

Nathan Eddy, PI, eddy@fnal.gov

Sasha Valishev, co-PI

Valeri Lebedev, co-PI

Alexey Burov

PURPOSE AND METHODS

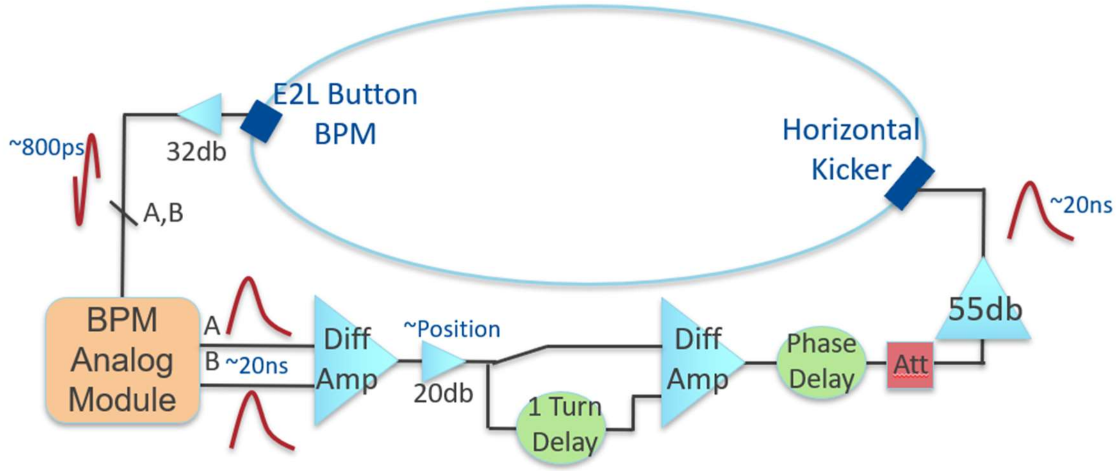
- Landau Damping provides damping mechanism via tune spread
- Octupoles provide a means to increase tune spread and increase the stable region via improved Landau Damping
- Octupoles introduce dependence of betatron frequency on betatron amplitude
  - Reduce dynamic aperture and lifetime
  - Landau damping sensitive to tails of beam
  - Can change chromaticity via feed-down effects
- This experiment is to study the effect of octupoles on instabilities produced by a transverse anti-damper (positive feedback) system which is used to mimic transverse beam instabilities.
- Initial experiments in Run I showed improved stability with octupoles but with limited data. Plan to improve statistics while improving experimental methods to collect data from all available instruments including TBT bpms, syncLight, wcm, and dcct.

BEAM CONDITIONS

- Need stored beam on nominal lattice, intensity >0.5mA
  - Nominal bunch length and transverse beam size
- Need to vary octupole string currents
- Need working bpms, syncL, wcm, and dcct
- Collect as much statistics as possible while varying beam current and octupole currents

APPARATUS

- Experimental setup



- Use horizontal button electrodes on E2L bpm with 32db RF pre-amplifier on each button
- BPM analog module based upon RF envelope detector conditions fast doublet into longer pulse – provides 32db of programmable gain control
- Implement 1 turn notch filter delay and phase delay with cable
- Use one plate of the horizontal strip-line to kick beam
- System improvements
  - Implement damper by simply swapping analog module for E2L
  - Ability to collect BPM turn-by-turn data
  - Matlab acquisition scripts to set gain and collect data (*.mat files)

RUN PLAN

- Experimental Data
  – Beam at nominal emittance - wait for beam to cool (~5min) or re-inject
  – Induce instability and collect TBT data
  – Repeat procedure with Octupoles powered – vary current
  – Repeat procedure with Non-linear magnet powered - vary strength (if possible)
- Shift 1 (~4 hours)
  – Commission anti-damper (timing and phase) – 30 min

– Commission Matlab data acquisition scripts – 30 min

– Collect experimental data with remaining time – 5 data points at each setting

- Analyze data for quality and anomalies
- Shift 2 (~4 hours)

Collect further data based upon analysis

ANALYSIS OF DAMPER OPERATION

In the transverse damper/anti-damper we use BE2L bpm for measurements of beam position and the horizontal kicker located shortly after injection Lambertson magnet. Twiss parameters at all BPMs and the involved optical elements are presented in the following Table. The damper electronics is located in the ESB building. That results in considerable delay in signal propagation leads that the signal is applied to the kicker 6 turns after the measurement. Note also that the damper uses a notch filter which effectively makes 7 turn delay to the kick after the first measurement.

Table: Twiss parameters at the IOTA BPMs, damper kicker and RF cavity.

	1	2	3	4	5	6	7	8	9	10	11	12	13
0	"NAME"	"S[cm]"	"BetaX"	"AlfaX"	"BetaY"	"AlfaY"	"DspX"	"DspXp"	"DspY"	"DspYp"	"NuX"	"NuY"	"-M56[cm]"
1	"START"	0	80.215	$3.546\cdot10^{-6}$	107.305	$3.032\cdot10^{-5}$	-24.575	$2.327\cdot10^{-5}$	-0.512	$-6.06\cdot10^{-3}$	0	0	0
2	"BA1C"	1.93	80.262	-0.024	107.34	-0.018	-24.575	$2.327\cdot10^{-5}$	-0.524	$-6.06\cdot10^{-3}$	$3.831\cdot10^{-3}$	$2.864\cdot10^{-3}$	$5.042\cdot10^{-5}$
3	"xKick1"	41.87	102.074	-0.522	123.643	-0.39	-24.574	$2.327\cdot10^{-5}$	-0.766	$-6.06\cdot10^{-3}$	0.077	0.059	$1.093\cdot10^{-3}$
4	"BA2R"	209.41	41.885	1.504	428.732	-3.421	-2.257	0.502	-1.452	$-9.738\cdot10^{-3}$	0.23	0.223	$5.468\cdot10^{-3}$
5	"BA3R"	286.58	82.678	1.363	129.554	-1.022	22.616	-0.5	-0.579	$8.397\cdot10^{-4}$	0.569	0.284	$7.483\cdot10^{-3}$
6	"BB1R"	485.28	206.065	1.467	205.93	1.466	$-9.373\cdot10^{-3}$	$3.949\cdot10^{-5}$	0.11	$4.756\cdot10^{-3}$	0.97	0.409	-1.75
7	"BB2R"	677.09	206.06	-1.467	206.18	-1.467	$-1.799\cdot10^{-3}$	$3.949\cdot10^{-5}$	1.023	$4.756\cdot10^{-3}$	1.28	0.719	-1.745
8	"BC1R"	921.32	63.011	1.122	202.291	-3.129	65.728	0.866	-1.076	-0.015	1.434	1.196	16.698
9	"BC2R"	$1.077\cdot10^{3}$	111.027	-1.659	84.719	0.833	122.996	0.517	0.631	$-1.737\cdot10^{-3}$	1.748	1.558	16.702
10	"BD1R"	$1.221\cdot10^{3}$	257.19	1.474	270.509	-2.188	119.713	-0.555	0.425	$-1.163\cdot10^{-3}$	1.83	1.841	-153.082
11	"BD2R"	$1.613\cdot10^{3}$	294.215	0.384	164.339	-0.356	-35.723	-0.389	-0.679	$3.198\cdot10^{-3}$	2.167	2.279	-153.072
12	"BE1R"	$1.721\cdot10^{3}$	105.79	0.953	350.847	-1.423	-29.94	0.491	-0.363	$2.666\cdot10^{-3}$	2.251	2.355	-133.573
13	"BE2R"	$1.875\cdot10^{3}$	380.233	-2.307	68.74	0.455	26.617	0.338	0.381	$5.366\cdot10^{-3}$	2.455	2.491	-133.569
14	"BE2L"	$2.121\cdot10^{3}$	382.546	2.316	68.29	-0.446	26.837	-0.338	0.375	$-5.505\cdot10^{-3}$	2.835	2.798	-133.563
15	"BE1L"	$2.276\cdot10^{3}$	107.694	-0.971	348.032	1.414	-30.41	-0.491	-0.388	$-2.56\cdot10^{-3}$	3.041	2.936	-133.559
16	"BD2L"	$2.385\cdot10^{3}$	295.752	-0.391	162.952	0.342	-34.944	0.389	-0.697	$-3.109\cdot10^{-3}$	3.124	3.014	-125.525
17	"arfc"	$2.582\cdot10^{3}$	192.071	-1.194	104.13	0.925	97.006	0.844	-0.807	$8.308\cdot10^{-3}$	3.346	3.167	-125.52
18	"BD1L"	$2.775\cdot10^{3}$	257.189	-1.474	270.509	2.188	119.672	0.555	0.444	$9.85\cdot10^{-4}$	3.46	3.449	-125.515
19	"BC2L"	$2.921\cdot10^{3}$	106.2	1.609	87.224	-0.863	122.217	-0.517	0.627	$1.566\cdot10^{-3}$	3.544	3.735	-223.117
20	"BC1L"	$3.075\cdot10^{3}$	63.009	-1.122	202.294	3.129	65.754	-0.865	-1.081	0.015	3.856	4.094	-223.113
21	"BB2L"	$3.316\cdot10^{3}$	216.344	1.52	216.467	1.52	0.052	$-2.757\cdot10^{-4}$	1.047	$-4.888\cdot10^{-3}$	4.007	4.569	-281.442
22	"BB1L"	$3.515\cdot10^{3}$	217.84	-1.527	217.703	-1.526	$-3.346\cdot10^{-3}$	$-2.757\cdot10^{-4}$	0.074	$-4.888\cdot10^{-3}$	4.323	4.884	-281.436
23	"BA3L"	$3.71\cdot10^{3}$	82.675	-1.362	129.555	1.022	22.59	0.5	-0.59	$-6.882\cdot10^{-4}$	4.721	5.006	-275.906
24	"BA2L"	$3.788\cdot10^{3}$	43.385	-1.542	425.384	3.407	-2.476	-0.5	-1.459	$9.886\cdot10^{-3}$	5.062	5.067	-275.904
25	"END"	$3.997\cdot10^{3}$	80.215	$3.772\cdot10^{-6}$	107.305	$3.055\cdot10^{-5}$	-24.564	$-4.761\cdot10^{-4}$	-0.502	$6.132\cdot10^{-3}$	5.291	5.29	...

In the first order of perturbation theory the damping rate of the damper is:

$$\lambda = \frac{ig}{2} e^{2\pi i \Delta \nu_{kp}} \left(1 - e^{-2\pi i \nu}\right) e^{-2\pi i \Delta \nu (1+n_d)} \tag{1}$$

where ν is the betatron tune, ν_{kp} is the betatron phase advance from kicker to pickup, n_d is the number of turns for the kick delay, and g is the gain of the damper. Large delay ($n_d = 6$) results in that the damping/antidamping has narrow tune width. Figure 1 shows the dependence of damping rate on the tune. Large delay between picking up the signal and its application to the kicker makes damping highly sensitive to the machine tune. As one can see from the figure the damping changes its sign outside [0.269, 0.335] window. Therefore for the cases where we introduce large non-linearity of octupoles an increase of betatron amplitude results in large dependence of betatron tune and amplitude and reduction of antidamping with betatron amplitude.

Large delay also limits maximum achievable damping rate. Numerical simulations show that for ν=0.3 the system becomes unstable for g = 0.295 and the maximum damping rate of 0.11 per turn is achieved for g = 0.083. Note that in difference to damping an increase of antidamping gain results in antidamping at any gain (in the absence of Landau damping) but the antidamping rate is slower than predicted by Eq. (1) if the gain is above ~0.05 (g < -0.05)

However, this dependence of the damping rate on the tune and the related limit on the octupole strength should not reduce the possibility of the experiment at the weak head tail regime, since the synchrotron tune is much smaller than the noted limit on the gain, $\nu_s \ll 0.05$.

Note also that large dispersion at the cavity location couples longitudinal and transverse motions. That results in that the damper noise excites not only horizontal motion but the longitudinal one as well. Numerical simulations support the phenomenon we found first experimentally.

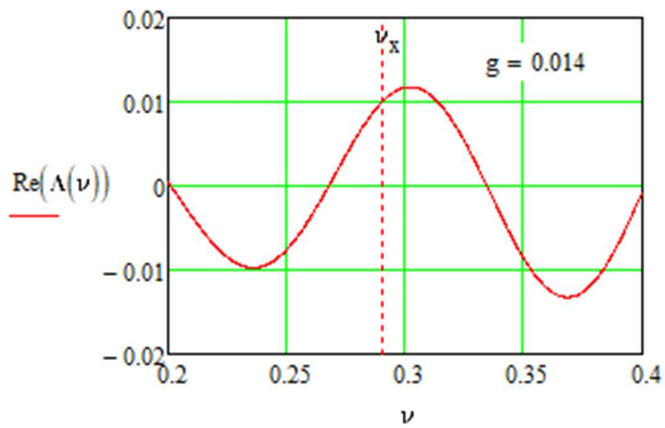


Figure 1: Dependence of damping rate of the horizontal tune for the damper in damping mode for the damper pickup BE2L.

FUTURE BEAM PHYSICS GOAL

In a longer run, the goal is to measure the stability diagram by means of the anti-damper with variable gain g and phase ϕ, as it was proposed by one of the participants and started recently to be studied at the LHC, https://arxiv.org/abs/2003.04383 . The diagram is suggested to be experimentally obtained as a set of threshold gains, measured for a sequence of phases and represented as $g\, e^{i\phi}$ on the complex plain. This goal requires the damper which satisfies the following conditions:

1. It sees only the entire dipole moment of the bunch $D = \int \lambda(s)x(s)ds$, where $\lambda(s)$ is the bunch line density as a function of the longitudinal coordinate s, and $x(s)$ is the transverse offset. The damper must be insensitive to the distribution of the dipole moment along the bunch.
2. The damper must mostly kick the bunch as a whole, with negligible variations of the kicks along the bunch.

For the beam, this experiment requires negligible chromaticity, so that the rms head-tail phase must be small enough, $\chi = \frac{|\xi|\sigma_s}{R\,|\eta|} \leq 0.05$, where ξ is the chromaticity, σ_s is the rms bunch length, $R = C/(2\pi)$ is the average ring radius, and η is the slippage factor. For typical IOTA parameters, with $\eta = 0.07$ and $\sigma_s = 20$cm, it requires the chromaticity $|\xi| \leq 0.1$.

As a first stage of this program, it is supposed to make that sort of measurements for a given phase of the anti-damper, to see what is the dependence of the threshold gain on the octupole strength for a given electron bunch, and then to see how this dependence vary with the bunch parameters, its current and emittances. It is crucial for this experiment to make such measurements for sufficiently small octupole strengths, to provide the weak head-tail conditions near the thresholds. In other words, the growth rate associated with the anti-damper only must be small compared with the synchrotron frequency.